Potential Impact of Long-Life Environmental Sonobuoys on Littoral ASW

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Abstract - The focus of military activity has recently shifted from large area engagements to regional conflicts. Consequently, supportive Naval maritime operations have continued to evolve toward littoral warfare in complicated shallow-water, near-shore environments. This evolution requires new sensors, advanced Concept of Operations, and improved data-analysis capabilities, among others. Planning operations in these harsh-environment areas is difficult because accurate predictions of tactical sensor performance depend on detailed knowledge of the local environmental conditions. Tactical mission planning is thus seldom optimal or efficient, often resulting in coverage gaps, increased risk, and reduced mission success. According to a Navy Mission Need Statement, "*Air ASW tactical execution, especially in littoral seas, requires in-situ environmental updates for preflight mission planning. In the conduct of ASW operations, an urgent need for explicit knowledge of environmental variables is required to optimize the effectiveness of operational acoustic sensors, as well as acoustic sensors in development.*"

The Naval Air Systems Command has considered extended-life environmental sonobuoy concepts to better characterize the littoral environment. Most designs contain a thermistor string to measure ocean temperatures and also hydrophones to measure ambient noise. This type of complex sonobuoy would be more expensive than a traditional single-measurement AXBT but it could provide a more thorough littoral environment assessment. This paper examines the trade-off between increased sensor complexity and improved ASW performance, in terms of cumulative detection probability.

Some advantages of an extended-life combined thermistor string/hydrophone approach, compared to AXBTs and tactical hydrophones, are: 1) higher accuracy of the raw data; 2) temporal averaging to smooth out fluctuations; 3) extended area coverage during drift; 4) less chance for surface temperature anomalies (*e.g.*, mixed-layer-depth errors) caused by various electronic and mechanical variability upon impact; 5) opportunities to discover thermal and acoustic feature boundaries during drift; and 6) less need to re-seed thus allowing longer tactical mission times. These advantages are evaluated relative to the following disadvantages: 1) increased cost; 2) potential drift outside the mission area; and 3) need for increased battery life for longer durations. The analysis is tempered by considering how a potential new system might be used.

One assumption is that an environmental sampling decision aid is available to determine the minimum number and best initial locations of drifting sensors to meet performance objectives. The November 2007 Requirements Document from the Naval Oceanographic Office states "*Sampling guidance: Development of guidance on the best way to deploy, spatially and temporally, observation systems in order to meet various forecasting, model assimilation, and model evaluation objectives is needed.*" Work in this area is reported in this Oceans '09 Conference in a paper entitled "Uncertainty-based Adaptive AXBT Sampling with SPOTS", which addresses optimal sampling requirements.

For this trade-off analysis, temperature data from water-sampling flights in the Sea of Japan off the east coast of Korea were used to simulate expected capability of a long-term drifting thermistor string. Then optimal initial positions for three notional buoys were determined followed by a simulation of drifting positions and data collected over 12 days. Ocean nowcasts were constructed and used to determine acoustic performance of a notional tactical sonobuoy field. The analysis shows that a drifting extended-life thermistor string can provide significant improvement in environmental characterization, tactical planning, and ASW detection performance.

I. INTRODUCTION

Naval operations continue to evolve toward Littoral Warfare as military action shifts to regional conflicts. To accomplish this evolution, new navigation, sensor, and data-analysis capabilities are needed to support operations in the highly variable and complicated near-shore waters of the littoral environment. Antisubmarine Warfare (ASW) is often conducted in shallow-water areas, where subsurface enemies pose a constant threat, and where knowledge of ocean thermal data and ambient noise levels is critical, but lacking. Planning operations in these harsh-environment areas is difficult because accurate predictions of sensor performance depend on detailed knowledge of the local conditions. Tactical mission planning is thus seldom optimal or efficient, often resulting in coverage gaps and increased risk. According to a Navy Mission Need Statement, "*Air ASW tactical execution, especially in littoral seas, requires in-situ environmental updates for preflight mission planning. In the conduct of ASW operations, an urgent need for explicit knowledge of environmental variables is required to optimize the effectiveness of operational acoustic sensors, as well as acoustic sensors in development.*" One solution is to deploy more environmental sensors (*e.g.*, Airborne eXpendable BathyThermograph; AXBTs) but this reduces time on-station available for the tactical mission.

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The Naval Air Systems Command has considered new ways to better characterize the littoral environment. One possibility is a new or upgraded extended-life sonobuoy with a thermistor string to measure ocean temperatures at fixed depths while drifting through an area. Additional sensors, like hydrophones to monitor the changing ambient noise field, are also possible alternatives. A new space-time sampling capability, like this, would be more expensive than a traditional single-shot, point measurement AXBT but it would provide valuable additional data for littoral environmental characterization. There would be many new requirements to meet and issues to solve for such a new device, like increased electrical power for long life, survivability, communications, processing, data rate, drift rate, Concept of Operations, etc. In addition, since higher resolution temperature fields would lead to better acoustic characterizations, there would be an opportunity to deploy complicated tactical buoy patterns that could be adapted to the environmental complexity and provide increased detection performance.

The increased unit cost would drive the need for an environmental decision aid to determine the minimum number and optimal deployment locations of environmental buoys to meet performance objectives. A prototype decision aid that addresses this issue has been developed and is reported elsewhere in the Oceans '09 Conference Proceedings. That capability, called SPOTS (Sensor Placement for Optimal Temperature Sampling) produces sampling patterns for AXBTs that are adapted to oceanographic conditions for optimal performance. Recent SPOTS results show that a few well-placed AXBTs can significantly improve temperature accuracy compared to larger numbers of gridded measurements.

Optimizing tactical buoy patterns for multistatic sensors has been addressed in several projects. The current accepted Fleet solution is called ASPECT. A recent research effort produced SCOUT (Sensor Coordination for Optimal Utilization and Tactics), which uses genetic algorithms to design non-standard buoy patterns and irregular "ping" intervals. Some results of this work are reported elsewhere in the Oceans '09 Conference Proceedings. They show that standard patterns are grossly ineffective in inhomogeneous environments where 36-60% improvements in detection performance are achieved with SCOUT and that 8-16 sonobuoys with SCOUT placement can perform as well as 32 regularly spaced sonobuoys.

The electrical power issue is being examined by the authors under a new research effort called SWEM (Sonobuoy Wave Energy Module) in which new technology is being developed to harvest kinetic energy from ocean waves and convert to electrical energy. There are many engineering challenges to be overcome. They include achieving adequate efficiency, performing well in all sea states, adapting to changing wave conditions, fitting in a fraction of the volume of a sonobuoy casing, surviving in rough seas, and being cost effective. That work is in an early research and development phase.

This paper addresses the potential tactical value of collecting drifting thermistor-string data. The additional value of measuring dynamic changes in acoustic ambient noise will be considered in future work. We assume that a SPOTS capability is available to determine the best initial deployment locations and that a SCOUT capability is available to locate tactical buoys in optimal locations. We further assume that a SWEM capability would allow at least a 12-day operational life. These results could help determine if a thermistor string on a new extended-life environmental sonobuoy has sufficient value to justify further research or a new development program.

II. ENVIRONMENTAL ANALYSIS

The analysis is based on AXBT data collected on 17 February, 23 February, and 1 March 1999 in the Sea of Japan, near the east coast of Korea. During each water-sampling flight about 44 measurements were made on an approximate 15-min grid (between 35.75 and 37.75 deg N and from near the coast to 130.5 deg E) and then assimilated into climatology using a standard set of optimal interpolation routines to produce temperature nowcasts throughout the water column. The spatial covariance distance for assimilation is often assumed to be the Rosby radius at the latitude of the measurement. In this analysis, for this dynamic enclosed sea, a smaller distance (approximately 20 km) is used. This smaller value is based on a previous analysis in this region.

Fig. 1 shows the results between 36 and 38 deg N at 100-m water depth on each of the three days, with temperature contours ranging from 4 to 12 deg C. Korea is colored gray and the exact AXBT deployment sites are shown by the nearly-gridded sets of white dots. The sampling density is sufficiently high that we consider these nowcasts to be "ground-truth" for comparison with other sampling schemes.

The contour shapes and intensities change dramatically with depth and over time during this 12-day period. We consider two questions: first, how well would these complicated temperature fields be represented by a small number of long-life drifting thermistor strings compared to a small number of fixed AXBT measurements; and second, are these environmental effects significant enough to affect tactical detection performance?

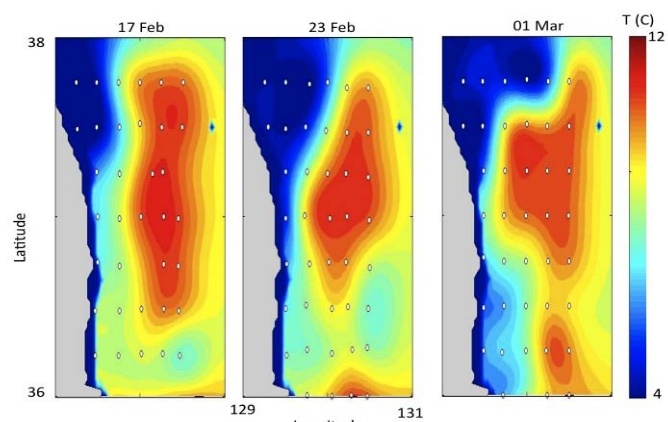

Figure 1. Ground-truth water temperatures in the Sea of Japan at 100-m depth on 17 Feb (left), 23 Feb (center), and 1 Mar (right).

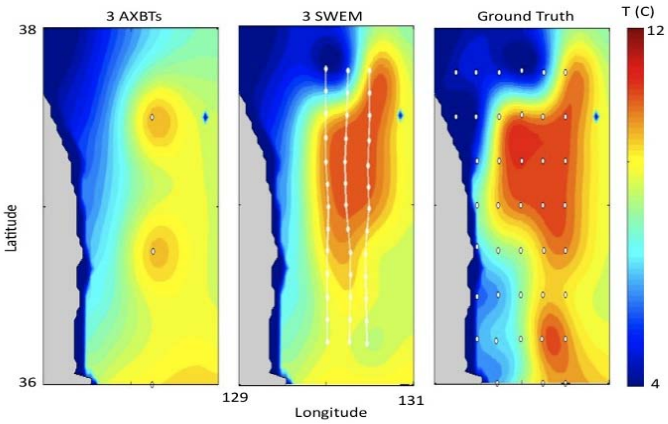

Figure 2. Temperature assimilation results on 1 Mar for 3 AXBTs (left), 3 SWEM buoys (center), and ground-truth (right).

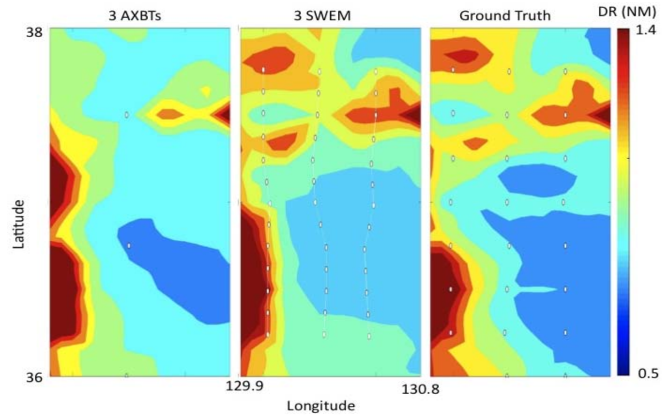

Figure 3. Detection ranges for a notional passive system at 300 Hz for a source and receiver at 200-m depth in the Fig. 2 environments.

The first question (sub-sampling) is addressed in Fig. 2 where we compare nowcasts from 3 AXBTs (left) and 3 hypothetical SWEM-powered buoys with thermistor strings (center) on 1 Mar. For simplicity, the conceptual extended-life drifting buoy system is called SWEM and for ease of comparison, the ground truth result for 1 Mar, already shown in Fig. 1, is repeated here (right). These nowcasts are for a 100-m depth, span 4 to 12 deg C, and are computed as follows.

For the AXBT assimilation, we assume that 3 measurements were made on a straight flight path at 36, 36.75, and 37.5 deg N along 130.25 deg E just prior to conducting a tactical mission. We further assume that the deployment process and analysis take 1 hr away from the tactical mission. The tactical consequence of the 1-hr environmental assessment is considered in the next section. The AXBT nowcast shows that at the 2 northern locations, the measurements were warmer than climatology, as shown by the circular orange areas, but not nearly as warm as the actual ground-truth temperatures.

For SWEM, we assume that on the first day of the measurement period (17 Feb), 3 SWEM buoys were deployed near the southern end of the 3 eastern-most columns of the ground-truth data. [The 3 AXBT samples are along the middle SWEM column.] We also assume about a ½ kt current flowing north so that after 12 days the SWEM buoys would be at the northern end of the ground-truth data. We then interpolate in space and time between the AXBT measurements and simulate the temperatures that would have been measured along the 3 northern moving tracks at daily intervals. The 13 simulated SWEM buoy locations along each of the 3 tracks are shown by white dots and lines in Fig. 2 (center).

We assume a 300-hr temporal covariance that weights down the data from early days (at southern positions) by more than half for the 1 Mar nowcast. Clearly the SWEM nowcast agreement with ground truth is significant, although it fails to describe the small southern warm core on 1 Mar at 36.25 deg N. In this case the SWEM samples at that latitude were simulated about 10 days earlier when that area actually contained a relatively cold core (see Fig. 1 on 17 Feb).

III. TACTICAL ANALYSIS

The second question (environmental impact on tactical performance) is addressed in this section. The three environments were used to predict sonar performance at 300 Hz for a notional passive system with source and receiver both at 200-m depth, assuming a uniform ambient noise distribution. The results are shown in Fig. 3 as a detection range map between 0.5 and 1.4 nmi for a slightly reduced set of longitudes between 129.9 and 130.8 deg E in order to avoid the very shallow water areas on the continental shelf to the west and the un-sampled areas to the east. The AXBT, SWEM, and ground-truth sampling locations are overlaid as white dots. Note that several columns of ground-truth measurements to the west are not visible in this reduced area.

In this case, 3 SWEM buoys clearly produce a better (*i.e.*, closer to ground-truth) acoustic representation than the 3 chosen AXBT locations, especially in the north. Part of the improvement results from the SWEM buoys being in the north near the day when the nowcast is calculated (1 Mar), while only one of the 3 AXBTs is in the north. However, the AXBT sampling strategy chosen is quite normal because it "covers" the area of interest on the day of interest. The longer detection ranges in the southwest occur over sloping bathymetry between the 200-m deep shelf and the 2000-m deep basin. The effect of temperature on detection over the slope is striking.

The final, and most important, calculation comes from an assessment of the Cumulative Detection Probability (CDP) over a search period with a set of passive tactical buoys. For this analysis we set up a search area from 36.5 to 37.85 deg N and 130 to 130.7 deg E (approximately 3200 nmi^2) and assumed that a 5-kt target was on a random patrol in this area. We used the SCOUT algorithms to choose optimal sensor locations for 8, 16, 24, and 32 sonobuoys but adapted them differently for the complexity of each environment.

We assume that an aircraft can be on-station for 8 hr and that the most accurate performance would be achieved when SCOUT optimizes to the ground-truth environment and searches for all 8 hr. The prediction, and actual mission result, for that case is the ground-truth CDP. In today's reality, SCOUT would optimize the tactical pattern based on the 3 AXBT measurements and then search for only 7 hr, since 1 hr would be needed to make and analyze the AXBT measurements. The predicted CDP for the 7-hr mission is expected to be less than the ground-truth CDP.

The results are shown in Fig.4 as CDP vs. number of tactical sonobuoys. In every case, the CDPs increase with the size of the sonobuoy field. The result for ground-truth (black line) has the highest CDPs and the result for 3 SWEM buoys (red line) is as good as ground-truth, except for the 32 tactical buoy case. The result for 3 AXBTs and a 7-hr search (green dashes) shows the lowest CDPs, as expected. Some of the reduction is due to the shorter search time and some is due to the poor environmental representation. For completeness, the result for a hypothetical case of 3 AXBTs and an 8-hr search is also shown (green line). The conclusion is that about half of the reduction in CDP is caused by the shorter search time and about half is caused by the poorer environment.

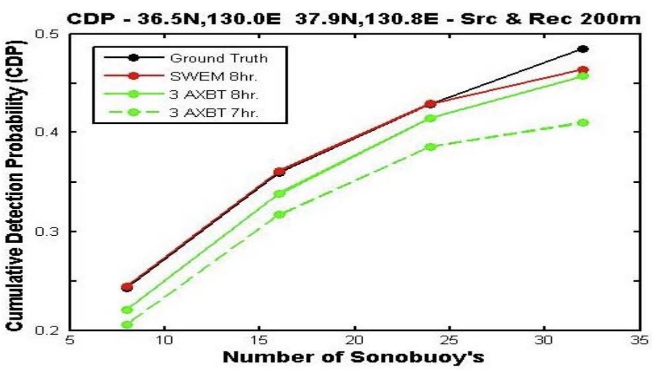

Figure 4. CDP results for 8, 16, 24, and 32 sonobuoys.

IV. SUMMARY

We studied the potential impact of drifting thermistor strings on tactical ASW performance using real AXBT data from water-sampling flights in the Sea of Japan. The results show that data collected over the previous 12 days from 3 drifting strings can significantly improve littoral environmental and acoustic characterization when compared to 3 discrete AXBT measurements on the day of interest. The analysis is based on comparing temperature nowcasts against a ground-truth data set and then comparing acoustic performance predictions at 300 Hz and detection probabilities for various sets of sonobuoy patterns. Half of the performance loss for the 3-AXBT case is caused by a reduced amount of search time available after deploying the AXBTs and the other half is caused by a poorer environmental description, compared to a drifting thermistor string.

These results support the concept of an extended life sensor based strictly on drifting temperature measurements. We believe that the level of support would increase significantly if one or more hydrophones were added because littoral ambient noise is highly variable and can easily be the dominant factor in detection performance. Future work will include a cost analysis and an attempt to determine if the performance gains are cost effective.

These results apply to summer in the Sea of Japan with 3 sensors. Generalized results will be obtained by extending the analysis to other seasons, locations, and number of sensors.

ACKNOWLEDGMENT

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